

Star formation in the Small Magellanic Cloud: the youngest star clusters

E. Sabbi · A. Nota · J.S. Gallagher · M. Tosi ·
L.R. Carlson · M. Sirianni · M. Meixner · L.J. Smith ·
M.S. Oey · R. Walterbos · A. Pasquali · L. Angeretti

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Abstract We combined optical *Hubble Space Telescope* ACS images with mid-infrared *Spitzer* data of the two young star clusters NGC346 and NGC602 in the Small Magellanic Cloud, to study how local and global conditions may affect the process of star formation. We found that, while general conditions such as metallicity, or the mass or morphological type of the parent galaxy do not strongly affect the process of star formation, local conditions such as the gas and stellar

density can affect both how star formation occurs and propagates, and also the evolution of a star cluster from early times.

Keywords Star formation · Cluster evolution · Magellanic Clouds

Introduction

Some of the nearby dwarf galaxies (such as the Small Magellanic Cloud; SMC) have evolved so slowly that they have preserved many of the characteristics expected of ‘young’ galaxies. These include low metal and high gas content, ongoing perturbations by neighbors, and a lack of organized rotation. The study of their star-formation history and chemical enrichment provides essential information to our overall understanding of galaxies.

Because of its close proximity (60.6 kpc; Hilditch et al. 2005), which allows for a quantitative and accurate census of its stellar content, the SMC is uniquely suitable to investigate in detail regions of star formation that have likely been formed by different mechanisms, such as stochastic self-propagating star formation (in the bar), supernova shock-waves, cloud–cloud collisions, cloud–gas shell interactions (in the wing), and galaxy–galaxy interactions (in the bridge). With the objective of understanding how local and global conditions can affect the star-formation (SF) process, we compared the properties two of the youngest SMC star clusters, NGC346 (in the SMC bar) and NGC602 (at the boundary between the SMC wing and the Magellanic bridge), as derived from deep images acquired with the Wide Field Channel (WFC) of the Advanced Camera for Surveys (ACS) on board the *Hubble Space Telescope* (HST).

E. Sabbi (✉) · A. Nota · M. Sirianni · M. Meixner
Space Telescope Science Institute, 3700 San Martin Drive,
Baltimore, MD, USA
e-mail: sabbi@stsci.edu

A. Nota · M. Sirianni
Research and Scientific Support Department, European Space
Agency, Baltimore, MD, USA

J.S. Gallagher
University of Wisconsin, Madison, WI, USA

M. Tosi · L. Angeretti
INAF–Osservatorio di Bologna, Bologna, Italy

L.R. Carlson
Department of Physics and Astronomy, Johns Hopkins
University, Baltimore, MD, USA

L.J. Smith
University College London, London, UK

M.S. Oey
University of Michigan, Ann Arbor, MI, USA

R. Walterbos
New Mexico State University, Las Cruces, NM, USA

A. Pasquali
Max-Planck-Institut für Astronomie, Heidelberg, Germany

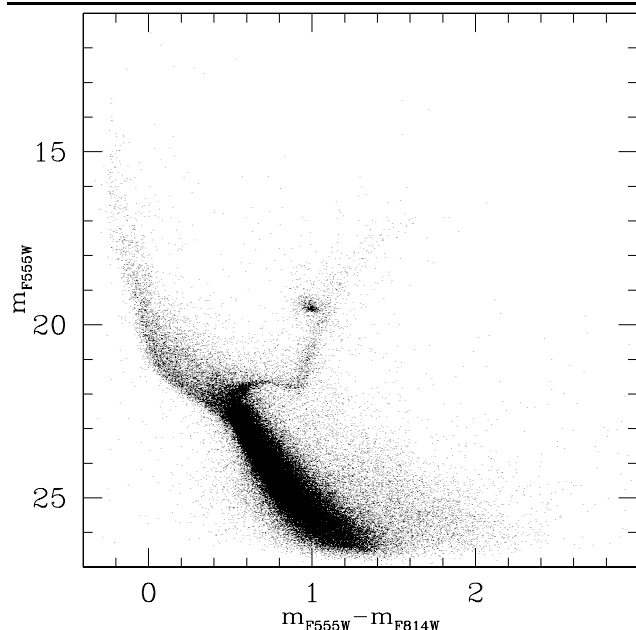


Fig. 1 NGC346 m_{F814W} versus $(m_{F555W} - m_{F814W})$ color-magnitude diagram

1 NGC346

NGC 346 is an extremely young (~ 3 Myr; Bouret et al. 2003; Sabbi et al. 2007) and active star cluster that excites the largest and brightest HII region (N66) in the SMC. NGC346 (J2000: $\alpha = 00^h59^m05.2^s$, $\delta = -72^\circ10'28''$) contains a major fraction of the O stars known in the entire SMC (Walborn 1978; Walborn and Blades 1986; Niemela et al. 1986; Massey et al. 1989). The bright end of its stellar population ($V \leq 19.5$ mag) has been investigated extensively in the past 20 years. Spectral investigations of the brightest members identified several stars of spectral type O6.5 or earlier (Massey et al. 1989; Heap et al. 2006; Mokiem et al. 2006; Evans et al. 2006). Massey et al. (1989) found the mass function (MF) of the brightest stars in NGC346—down to $5 M_\odot$ —to have a slope that is consistent with what has been found for massive stars near the Sun and in the Large Magellanic Cloud (LMC).

1.1 NGC346 color-magnitude diagram

Figure 1 shows the m_{F814W} versus $(m_{F555W} - m_{F814W})$ color-magnitude diagram (CMD) of all stars identified in the WFC NGC346 data with photometric errors < 0.1 mag. We can distinguish, in this CMD, the different stellar populations that coexist in the region, and that indicate that the star-formation history of the region where NGC346 is located is quite complex:

- A rich old stellar population, with a main sequence (MS) extending from $m_{F814W} \simeq 22.0$ mag down to $m_{F814W} \simeq$

25.5 mag. The evolved stars of this population clearly define the red giant branch (RGB), with the brightest stars at $m_{F814W} \simeq 15.0$ mag, and a tight red clump (RC) at $m_{F814W} \simeq 18.5$ mag. The narrow subgiant branch (SGB), visible at $m_{F814W} \simeq 21.0$ mag in the color range $0.45 \leq (m_{F555W} - m_{F814W}) \leq 0.95$ mag, indicates that, in the NGC346 region, the old stellar population is dominated by the presence of the BS90 star cluster. The presence of SGB stars, both fainter and brighter than the BS90 SGB, indicates that, in the field, SF occurred before and after the formation of this star cluster (Sabbi et al. 2007).

- A young population. The bright ($12.5 \leq m_{F814W} \leq 22.0$ mag) and blue ($-0.3 \leq (m_{F555W} - m_{F814W}) \leq 0.4$ mag) MS, clearly visible in the upper left of the CMD, is the most remarkable feature of the youngest stellar population. The majority of these stars belong to NGC346, and have an age of ~ 3 Myr (Bouret et al. 2003; Sabbi et al. 2007). Spectral analysis of NGC346 members revealed the presence of stars as young as ~ 1 Myr, (Massey et al. 2005), but stars aged ~ 5 Myr are also present (Heap et al. 2006; Mokiem et al. 2006).
- Hundreds of pre-main-sequence (pre-MS) stars in the mass range $0.6\text{--}3 M_\odot$ are visible between $0.6 \leq (m_{F555W} - m_{F814W}) \leq 2.2$ mag, and below $m_{F814W} \simeq 22.0$ mag, suggesting that star formation is likely still active in the region Nota et al. (2006). *Spitzer Space Telescope* (SST) observations also detected a myriad of embedded young stellar objects (YSOs) scattered across the entire region (Bolatto et al. 2007). This recent stellar population does not appear to be uniformly distributed within the ionized nebula, but is rather organized in many, likely coeval, subclusters (Sabbi et al. 2007) that are coincident with clumps of molecular gas previously detected by Rubio et al. (2000). Simon et al. (2007) noted that almost all subclusters host one or more YSOs.

1.2 NGC346: present-day mass function

The high sensitivity of the *HST*/ACS allows us to investigate the stellar content of NGC346 from $\sim 60 M_\odot$ down to $\sim 0.6 M_\odot$, making NGC346 one of the few known regions where a MF can be determined over two orders of magnitude (the other classical case being the Orion Trapezium Cluster in our own Milky Way; Elmegreen 2006).

As discussed earlier, there is evidence that NGC346 formed stars over the last 5 Myr. Furthermore, hundreds of stars in NGC346 are still in the pre-MS phase (and, therefore, their luminosity strongly depends on age), and star formation is still ongoing (Bolatto et al. 2007; Simon et al. 2007). To overcome the age-luminosity degeneracy that characterizes NGC346 data, we applied the technique presented by Tarrab (1982) and Massey et al. (1995), which

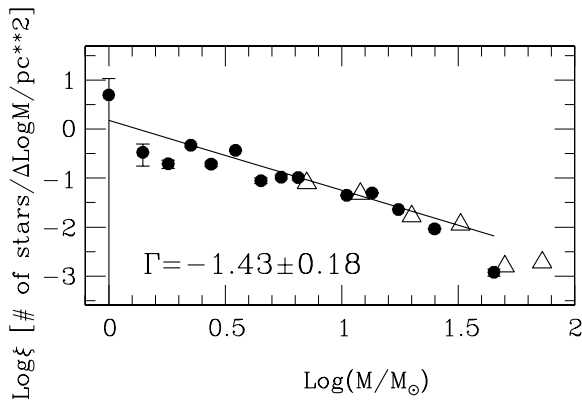


Fig. 2 NGC346 MF in the mass range from 0.8 to 60 M_{\odot} , after the subtraction of the contribution by the star cluster BS90 and the field of the SMC. Open triangles represent the IMF determined by Massey et al. (1989)

consists of directly counting the stars between two theoretical evolutionary tracks, according to their position in the Hertzsprung–Russell diagram (HRD).

A weighted least mean square fit to the data indicates that, between 0.8 and 60 M_{\odot} , the slope of the NGC346 MF—after statistical subtraction of the SMC field contamination—is $\Gamma = -1.43 \pm 0.18$ (Fig. 2), in good agreement with the value derived by Salpeter for the initial mass function (IMF) in the solar neighborhood (among the various parameterizations of the MF, we chose the one proposed by Scalo (1986), where the MF is characterized by the logarithmic derivative, $\Gamma = d(\log \xi(\log(m)))/d \log m$, with $\xi(\log(m))$ representing the MF and Γ its slope. The reference IMF, derived by Salpeter (1955) for the solar neighborhood, has a slope $\Gamma = -1.35$). Furthermore we note that, as already derived by Massey et al. (1989), the MF is quite steep above 5 M_{\odot} (we derive a slope $\Gamma = 1.87 \pm 0.41$ for this mass range), and becomes flatter below this mass. A detailed discussion of the uncertainties that may affect the derived MF slope is presented in Sabbi et al. (2008).

The high spatial resolution and the depth of our photometric data have allowed us to study in detail the spatial variations of the MF in four annuli (annuli 1, 2, 3, and 4) with projected distance from the NGC 346 center $R \leq 4.00, 9.00, 14.00$, and 19.80 pc. Less than 2.6 stars pc^{-2} belong to NGC346 outside ~ 20 pc from the center (Sabbi et al. 2008). MFs derived for annuli 1, 2, 3, and 4 are shown in Fig. 3. In the innermost region, the MF appears quite flat, with $\Gamma = -1.03 \pm 0.14$. It becomes steeper when moving from the center to the periphery, where its exponent becomes $\Gamma = -2.08 \pm 0.14$.

We applied a Kolmogorov–Smirnov (K-S) test to verify the significance of the differences found between the MF obtained in the innermost annulus (annulus 1) and those derived for the other three annuli. According to the K-S test, the probability that the MFs derived in annuli 2, 3, and 4 are

drawn from the parent distribution of the MF in the innermost annulus is 3.9, 0.3, and 0.06%, respectively. Therefore, we can safely exclude that regions 3 and 4 are drawn from the same parent distribution as region 1.

The projected density of massive stars from the innermost annulus to the periphery decreases by a factor of 60, whereas low-mass stars are depleted only by a factor of 6, indicating that the change in the MF slope is due to a lack of massive stars in the periphery, rather than an excess of low-mass stars there.

As discussed by Sabbi et al. (2007), NGC346 exhibits a very complex morphology, with the stars assembled in many coeval subclusters. Due to a lack of information on the dynamics of the subclusters, to zeroth order we can consider all stars in NGC346 as members of an individual star cluster. Comparing the age of NGC346 with its mass-segregation time scale (T_{msg}), we found that T_{msg} is one order of magnitude larger than the age of NGC346, supporting the idea that the observed segregation of the massive stars is likely due to initial conditions, rather than to dynamical evolution (Sabbi et al. 2008). Furthermore, Sabbi et al. (2007) suggested that NGC346 is probably the result of the collapse and subsequent fragmentation of the initial giant molecular cloud into multiple ‘seeds’ of SF. If this is the case, the fact that the various ‘seeds’ of star formation are still distinguishable would imply that NGC346 is not yet completely relaxed, and that the majority of the stars would still be close to their birth positions. Also in this case, the observed mass segregation would be primordial and would thus represent a feature of the way the cluster is forming (Sabbi et al. 2008).

2 NGC602

Very little is known about the young cluster NGC602 (J2000: $\alpha = 01^{\text{h}}29^{\text{m}}31^{\text{s}}$, $\delta = -73^{\circ}33'15''$), first detected by Dreyer (1888) and classified as a cluster by Lindsay (1958). It is located in the wing of the SMC, a region of low gas and stellar content, far from the main body of the galaxy but assumed to display the same chemical characteristics, i.e., $Z \sim 0.004$ (Lee et al. 2005). This region contains a population of hot and young (10–60 Myr-old) stars (Westerlund and Glaspey 1971; Demers and Battinelli 1998; Courtes et al. 1995; Massey et al. 2000).

2.1 NGC602 color-magnitude diagrams

We use CMDs as a primary method of identifying the stellar populations present in the region. The m_{F555W} versus ($m_{\text{F555W}} - m_{\text{F814W}}$) CMD of the region shows a very well-delineated MS down to $V = 26.5$ mag (Fig. 4). The upper part of the MS indicates the presence of a very young population. The lowest part of the MS has the characteristics of

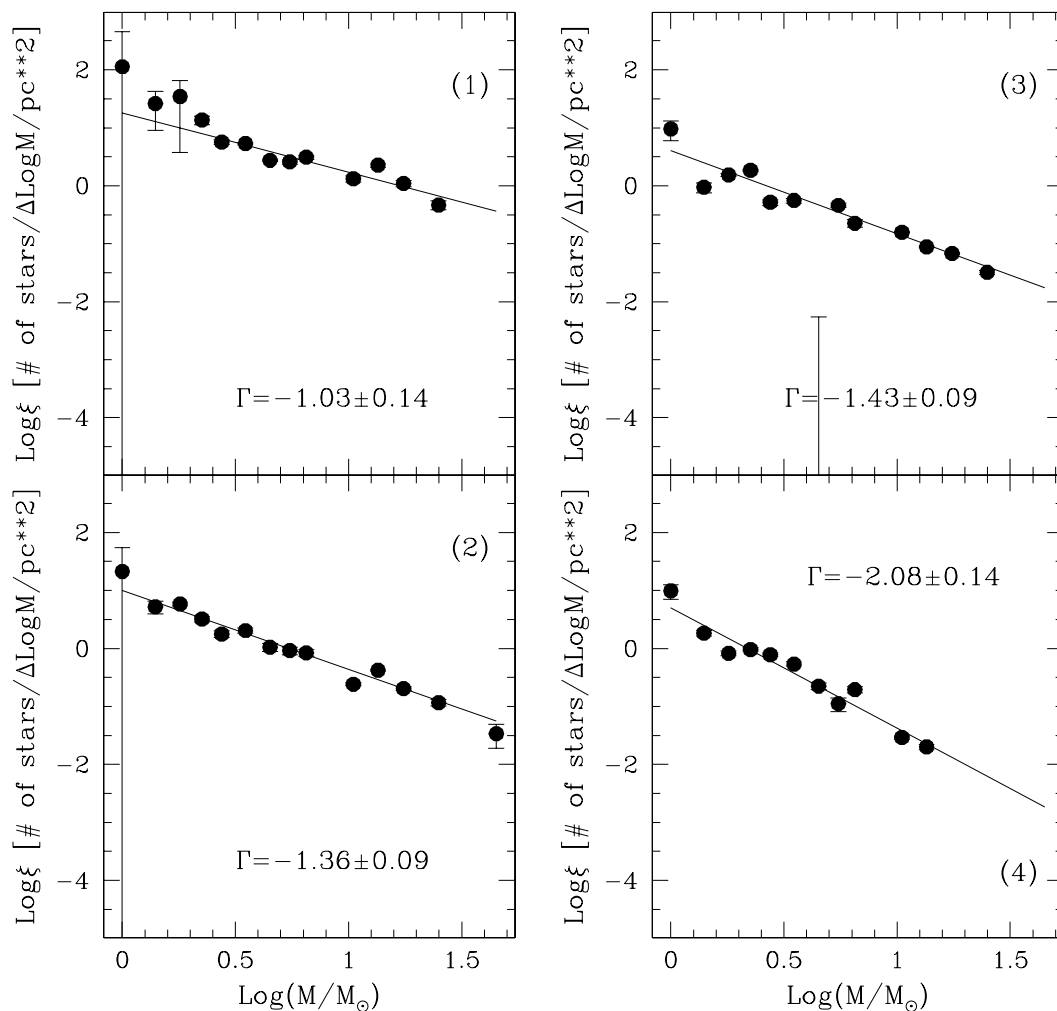


Fig. 3 MFs of the four regions of NGC346 analyzed in this paper: in panel (1) we present the MF derived within 4 pc from the cluster center, panel (2) shows the MF obtained between 4 and 9 pc; the MF

obtained between 9 and 14 pc is shown in panel (3), and in panel (4) we show the MF corresponding to the annulus between 14 and 20 pc

an older population, most likely the background field of the SMC. The MS turn-off is outlined, but not very well populated, and there is an indication of a RGB and of a RC (at $V = 19.5$, $V - I = 1$ mag). In addition, we detect a sizable population of faint and red stars located to the right of the MS ($V > 22$, $1 < V - I < 2$ mag). The magnitude and color of this group of stars is consistent with their nature of low-mass ($0.6\text{--}3 M_{\odot}$) pre-MS stars.

The ages of these different stellar populations have been estimated using isochrone fitting: we derive an age of ~ 5 Myr for NGC602. An older population, dated at ~ 6 Gyr and consistent with the SMC field, is also present (Carlson et al. 2007).

SST/IRAC data allowed us to sample a YSO population, younger than the one we detect in the optical images. We have constructed five CMDs, combining our IRAC observations and the YSO model points for stellar masses greater

than about $6 M_{\odot}$ from Whitney et al. (2004). From the analysis of the mid-infrared CMDs, we identified 25 good YSO candidates. Our YSO candidates fall in the same color-magnitude space as Class 0.5 and Class I YSO models, indicating that we are finding a second, possibly still ongoing, stage of star formation (Carlson et al. 2007).

We compared the spatial distribution of the pre-MS stars detected in the optical images and the YSOs selected from the infrared data set. The distribution of the pre-MS stars is concentrated in the center of the cluster, where the brightest and most massive stars, of O and B spectral types, are also found (Massey et al. 2000). Outside the central cluster, pre-MS stars appear generally concentrated in compact, structured groups, similar to the subclusters detected in the NGC346 region (Nota et al. 2006; Sabbi et al. 2007). The younger YSOs detected in the IRAC images appear to have a different spatial distribution. Overall, they are further away

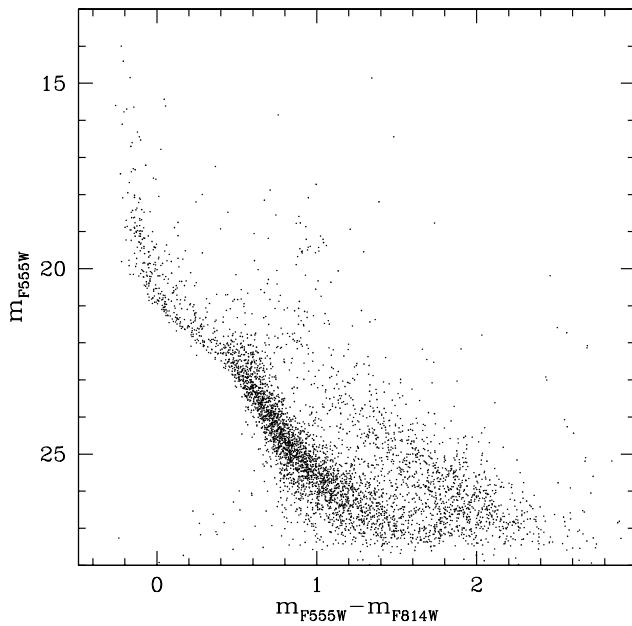


Fig. 4 NGC602 CMD, m_{F555W} versus $(m_{F555W} - m_{F814W})$

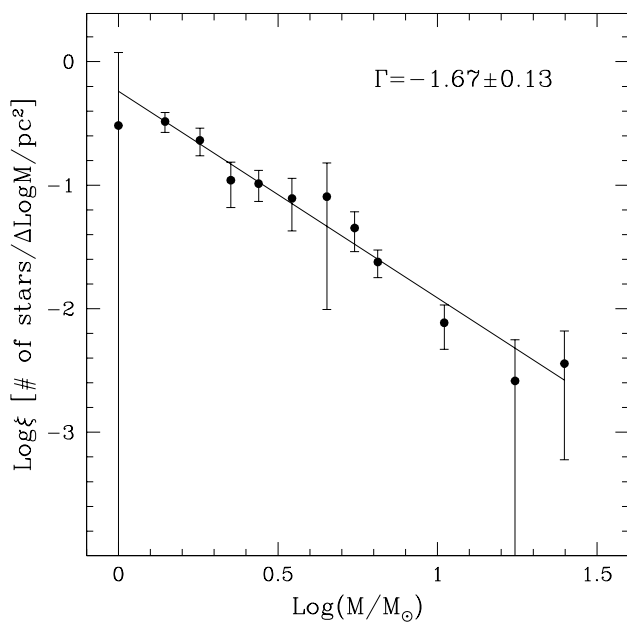


Fig. 5 NGC602 MF in the mass range between 0.8 and $30 M_{\odot}$ after statistical subtraction of the contributions from the field of the SMC

from the cluster center. They mostly appear concentrated along two dusty ridges towards the NW and SE, indicating that along these two structures star formation is active and progressing (see Plate A in Carlson et al. 2007). We do not find many YSOs in the cluster center, as could be expected, since the powerful winds of the most massive stars appear to have effectively removed dust and gas from this inner region.

2.2 NGC602: present-day mass function

As in the case of NGC346 (Sect. 1.2), we derive the NGC602 MF (Fig. 5), by counting the stars between two theoretical evolutionary tracks. Using a weighted least mean square fit to the data, after the statistical subtraction of the contributions from the field of the SMC, we derive a slope $\Gamma = -1.67 \pm 0.13$ for the NGC602 MF, in good agreement with the value derived by Salpeter for the solar neighborhood. We also looked for evidence of mass segregation in NGC602. Although we find that the MF is flatter in the center ($\Gamma = -1.08 \pm 0.33$) and becomes steeper in the periphery ($\Gamma = -1.53 \pm 0.15$), the poor statistics of the data do nevertheless not allow us to distinguish any significant spatial variation in the NGC602 MF (Cignoni et al. 2009).

3 Conclusions

We have analyzed the process of star formation in two of the youngest star clusters in the SMC. By combining *HST*/ACS–optical data with *SST*/IRAC mid-infrared images, we were able to investigate how star formation occurs and propagates within a star cluster over many Myr.

Our analysis of the stellar content of NGC346 and NGC602 indicates that, within all the uncertainties that can affect the determination of a MF, the MF slope of these clusters, at least down to the solar-mass regime, is consistent with the value derived by Salpeter (1955) for the IMF in the solar neighborhood, further supporting the notion that the stellar MF does not strongly depend on the metallicity, the mass or morphological type of the parent galaxy.

Sabbi et al. (2007) noted that stars in NGC346 appear to be organized in several coeval subclusters, embedded in HII regions, and coinciding with the CO clumps analyzed by Rubio et al. (2000). YSOs between Class I and Class III are found in 14 of the 16 subclusters identified (Simon et al. 2007). The subclusters are also connected by filaments and arcs of gas and dust. The complex structure of NGC346 and its young age, compared to the relevant dynamical time-scales, suggest that NGC346 is not dynamically evolved, and probably not yet relaxed. On the basis of these considerations, we conclude that NGC346 can result from the collapse and subsequent fragmentation of an initial giant molecular cloud in multiple nearly coeval ‘seeds’ of SF, and that the observed segregation of the most massive stars is likely primordial.

The combination of deep optical *HST*/ACS images and infrared *SST*/IRAC images of NGC602 has provided an interesting time sequence of star-forming events in this young cluster. The high-resolution optical data have shown a rich population of low-mass (0.6 – $3 M_{\odot}$) pre-MS stars, that formed coevally with the cluster about 5 Myr ago. Conversely, the brightest sources detected in the infrared images

have magnitudes and colors consistent with state-of-the-art model YSOs of class 0.5 and I. These objects have a typical lifetime of 10^5 – 10^6 yr, indicating that the region has likely undergone two subsequent episodes of star formation: the primary one, 5 Myr ago, that formed the central cluster, the most massive stars, and the pre-MS stars we detect in the optical images; and a more recent one, ~ 1 Myr ago, that formed the class 0.5 and I YSOs detected in the *SST/IRAC* images. The youngest objects are spatially located far from the central cluster, along the two dusty ridges. The crossing time from the cluster center to the two ridges is between 1 and 2 Myr, and it is very plausible that the secondary episode of star formation has been triggered by the instabilities caused by the formation of the central cluster. It is also likely that star formation is still actively continuing in the region of the ridges, where gas and dust seem to be still abundant.

The differences between the star-formation history of NGC346 and NGC602 therefore seem to suggest that local conditions (e.g., gas and stellar density, shock fronts from supernova explosions, cloud–cloud collisions, etc.) can affect how star formation occurs and how star clusters evolve from their very beginning.

Appendix: Discussion

Barbá: HD5980 (a triple WR system) and Sk80 are probably the most massive stars in the area. These stars are located well outside the core of NGC346. The OB association to which these stars and the supernova progenitors belong could provide the energy for the triggering of the star formation in NGC346. HD5980 provides 50% of the flux in the area.

Sabbi: Both the supernova rate and the HD5980–Sk80 association are too young to be the trigger: spectroscopic and photometric observations indicate that NGC346 has formed stars over the last 5–6 Myr.

Silich: Do you have some physical explanation for the ‘primordial’ mass segregation?

Sabbi: The comparison between the relaxation time for the most massive stars (10 Myr) and the age of NGC346 (~ 3 –5 Myr), combined with the very low dispersion velocities of the most massive stars (Niemela et al. 1986), both seem to indicate that the most massive stars formed *in situ*.

Whitmore: Have you considered the possibility that the older (~ 15 Myr) cluster in the upper left of the NGC346 image may be the main trigger? For example, is the distance to the younger clusters consistent with a shock travel speed of 20 – 30 km s^{-1} typically seen?

Sabbi: No, we don’t think that SC-16 can be the trigger of SF in NGC346, as its projected distance from the center of NGC346 is ~ 40 pc.

Fritze: Regarding NGC602, what about masses of YSOs now forming at the periphery as compared to (older) stars in the centre? Are they of lower mass? In other words, do we see a sequence in the sense that massive stars form first and in the centre and lower-mass stars form later and farther out?

Sabbi: Yes, the candidate YSOs in the periphery of NGC602 are consistent with low-mass objects.

Alves: Is star formation on the edges of NGC602 substantial or residual? Would you say triggering is an important process in this cluster?

Sabbi: We have not yet derived the star-formation rates (SFRs) for the two generations of stars identified in NGC602, so it is not possible to establish if the star formation on the edge of NGC602 is residual or otherwise. On the basis of what we observe, triggering seems to play an important role, but in order to quantify it we need to derive the SFRs.

Elmegreen: By density, do you mean stars per cubic pc? So, the high-density cluster was more hierarchical?

Sabbi: What we derived is the surface stellar density (stars per square pc), and yes, according to what we observe the high-density cluster was more hierarchical.

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